National Institute of Standards and Technology

Cleanrooms in NIST's Programs: Review and Analysis

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Executive Summary

The 30- to 45-year-old facilities of the National Institute of Standards and Technology cannot adequately support the Institute's mission of providing world-class research, measurements, and standards for U.S. industry and science. For more than 10 years, NIST scientists have been coping with steadily deteriorating environmental conditions in these facilities that reduce the accuracy of precision measurements, lower research productivity, and at times prevent important research from being undertaken.

Planning Background

In February 1998, NIST delivered to Congress an updated Facilities Improvement Plan designed to help remedy the technical obsolescence of its facilities through construction of new facilities and major renovation of existing buildings at both its Gaithersburg, Md., and Boulder, Colo., sites.

Since NIST's initial report to Congress on facilities in 1992, progress has been made. An Advanced Chemical Sciences Laboratory has been constructed and will be occupied as of March 1999. A number of projects to ensure the safety, capacity, maintenance and major repair of NIST's buildings on both campuses have been completed or initiated. The design for an Advanced Measurement Laboratory (AML) in Gaithersburg was completed in 1996 at a cost of $17 million. This laboratory would provide the exceptional levels of environmental control of air cleanliness, humidity, temperature, vibration, and electrical power quality required for NIST's most technically demanding research areas (see Appendix A). The total estimated construction cost of this project is $203.3 million. The President's FY 2000 budget contains a request for $95 million, which combined with previous appropriations, would allow NIST to begin construction of the AML in FY 2000.

A key technical feature of the AML is an advanced cleanroom facility. In the longer term, NIST's facilities plan also calls for construction of additional cleanroom space to meet the needs of the technical programs in Boulder (this facility is not yet budgeted). In its FY 1999 report, the Senate Appropriations Committee directed NIST to review its programs requiring regular cleanroom use and to report, to the committee, on the feasibility of consolidating these programs before funds for construction of cleanrooms are spent in either Gaithersburg or Boulder. This report addresses the committee's request.

The Growing Need for Cleanrooms

The need for cleanroom space has grown dramatically in the last 10 years. Modern research routinely operates on the tiniest of scales. When NIST's facilities were constructed, measurements were typically made at the part-per-thousand and occasionally the part-per-million level. Today, measurements at the part-per-million level are routine, and laboratory research typically operates at the part-per-billion level and below. This dramatic shrinking of size scales demands exceptionally clean air. Dust particles, gaseous molecules, flakes of skin, or even an eyelash can wreak havoc with a wide range of research, from testing of air filters for environmental contaminants to studies of the nanoscale (billionth of a meter scale) properties of materials. It is estimated that in just 60 seconds a motionless person may generate as many as 100,000 particles (skin flakes, salt, oils, moisture, droplets, even deodorant) of a size large enough to damage an integrated circuit.

Cleanrooms allow researchers to cope with the inherently dirty air around us. These special laboratory facilities screen out airbone particles with high efficiency filters. The most advanced cleanrooms also are designed with ceiling to floor airflow so that any particles generated will fall quickly to the floor and be filtered out. Researchers working in these rooms wear special suits to help prevent fibers from clothes and skin flakes from entering the air. Special materials are used on counters and walls to provide easily cleaned, static-free surfaces. There is a sliding scale standard for "cleanliness" in cleanrooms. The permitted density of particles in a cleanroom can vary by a factor of 100 million depending on the room's class—e.g., 10, 1,000, or 100,000. Each rating designates the number of allowable particles of a particular size in one cubic foot of cleanroom air—the lower the class, the cleaner the air.

Cleanrooms can be expensive compared to general-purpose laboratories, but this really applies only for facilities constructed to achieve a certifiable condition at the highest level (class 100 and better). What can be extraordinarily expensive is trying to retrofit the required air handling equipment for cleanrooms at the level of class 100 and better into existing space. For this reason, the clean-room facility in the AML has been designed for, and will be limited to, those programs requiring space that could be certified as class 100 or better.

It is well known that rapid obsolescence of cleanroom space is a fact of life in the semiconductor industry. This refers, however, to the very specialized fabrication operations that may take place within the industrial cleanroom. The facilities required for a large-scale specialized semiconductor chip manufacturing operation do indeed change every few years, if not even more frequently. But the basic cleanroom can function well for many years, even decades, particularly in a research, as opposed to a manufacturing environment. Research programs will change and modifications may be needed as a result, but if the cleanroom is designed with flexibility in mind, it isn't a major problem to make the changes.

Review of NIST's Clean Facilities

Since receiving the committee directions, NIST has conducted a review of its use of cleanroom space on both the Gaithersburg and Boulder sites.

The review found that about 12,500 net square ft (nsf) of laboratory space on the Gaithersburg site qualify as cleanrooms and other specialized clean space. The laboratory space in Boulder includes about 6,000 nsf of clean space. Another 4,600 nsf on both sites is devoted to operational support space. In addition, at least 38 laboratories contain smaller special purpose clean spaces, e.g., hoods and glove boxes.

The space devoted to cleanrooms and support space constitutes only about 3 percent of NIST's total laboratory space (6 percent if the laboratories that house clean zones are included). But the use of this space is widespread—excluding the Information Technology Laboratory—NIST's Measurement and Standards Laboratories are organized into 37 technical divisions, and more than half (20) of these divisions require clean space to conduct their work.

NIST's most recent review of its cleanroom needs found that 60 percent of the research groups requiring cleanroom space report that their current facilities are inadequate to produce research results needed by U.S. industry and science, and inferior to comparable space available in academia, industry, and NIST's counterpart organizations worldwide. Of the remaining 40 percent, roughly half say they have adequate facilities today but anticipate more stringent requirements in the future. The situation is so inadequate in some cases that researchers cannot accept samples for analysis from high-tech industrial labs because they might be ruined by NIST’s unacceptably dirty air.

Planned Cleanroom Facilities

Measurement science in support of advanced technology that increasingly underpins the U.S. economy requires ever more stringent control of environmental conditions such as temperature, humidity, vibration, airflow, and cleanliness. It is not economically feasible to retrofit existing space to meet these requirements. Structural limitations of the existing general-purpose laboratories effectively prevent achieving the necessary headroom, flexibility, and overall performance levels of an AML-grade laboratory. The cleanroom planned for the AML will provide about 12,000 nsf of new cleanroom space, bringing the total Gaithersburg cleanroom space to about 24,500 nsf. The facility was sized to be adequate for existing programs on the site. Significant new program demands would require additional facilities.

In the needs assessments conducted over the last 10 years (see Appendix B), requirements for additional high-quality clean space in Boulder consistently have been found to be comparable to those in Gaithersburg. Boulder programs requiring high-quality clean space include work on high-speed microwave electronics, diode lasers, voltage standards, nanoscale cryroelectronics, superconducting electronics, magnetic recording metrology, and semiconductor optoelectronic devices. Six of Boulder's seven research divisions require such space. There is no significant technical overlap between the research activities of any of these six divisions and Gaithersburg programs.

Consolidation of Cleanroom Facilities

NIST concludes that it would not be programmatically sensible, cost effective, or technically appropriate to consolidate all NIST programs requiring regular cleanroom use at one site.

- It would produce no significant increase in technical synergy between NIST programs.
- It would entail significant net cost, in dollars, program disruption, and intellectual assets, to relocate even the minimum number of technical staff.
- It would require the construction of a separate new cleanroom facility in Gaithersburg, plus additional office and laboratory space.

NIST's plans include the building of a general-purpose cleanroom facility at both of its sites because the need for cleanroom space pervades modern technology. The ultimate beneficiaries will be the U.S. economy and science through higher quality NIST reference materials, improved measurements, and faster access to NIST research advances.

Introduction and Background

NIST's 30- to 45-year-old laboratory facilities cannot adequately support NIST's mission. For more than 10 years, NIST scientists have been working in laboratories that increasingly fail to meet the technical challenges presented by the present and future of measurement science. There is no better example than the quality and quantity of cleanrooms and other environmentally controlled spaces available to NIST researchers.

In response to this performance shortfall, NIST has developed a facilities master plan that includes new construction and renovation at its two major sites, Gaithersburg, Md., and Boulder, Colo.. A summary Facilities Improvement Plan was sent to Congress in February 1998. Central to NIST's plan is a new building called the Advanced Measurement Laboratory (AML).

The design for the AML, completed in 1996, requires some review and revision to take into account certain updated safety features, code requirements, and some minor research-driven changes. Funds to construct the AML are requested in the President's budget for FY 2000. Additional background on the history of the development of the AML project can be found in Appendix A.

A key technical feature of the AML is an advanced cleanroom facility. In the longer term, NIST's Facilities Improvement Plan also calls for improved cleanroom facilities in Boulder. The Senate Appropriations Committee report for FY 1999 contained the following language:

The agency should consider consolidating at one location all programs requiring regular use of a clean room. The Committee directs NIST to review programs requiring regular clean room use and report to the Committee about the feasibility of program consolidation supporting the construction of a clean room at one site before expending funds for construction at either site.

This report summarizes the results of that review.

What is a "Cleanroom"?

Most simply put, a cleanroom is any enclosed room-sized space designed to minimize the number of particles in the air, but the word covers a very broad and diverse range of facilities. Normal air in offices and homes averages between 2 million and 10 million particles per cubic foot. These particles are seen easily as the sun streams through cracks in window blinds. While the average person breathes these particles in and out all day with no ill effects, many research and manufacturing settings require much cleaner air to function. Cleanrooms provide this cleaner air by filtering out all particles larger than 5 micrometers (µm) and some portion of particles between 0.1 and 5 µm.

Overview

Cleanrooms are rated with different classes depending on the number of particles allowable of a certain size within a cubic foot of air. A class 1,000 cleanroom has approximately 1,000 particles of 0.5 µm for each cubic foot of air. According to the current U.S. standard, cleanrooms are rated as class 1, 10, 100, 1,000, 10,000, or 100,000 depending on the number of particles 0.5 µm allowable within a cubic foot of air. The International Standards Organization (ISO) is developing a standard that adds three more levels of cleanliness (two below 1, and one above 100,000), and uses metric equivalents to these classifications.

Scale size is a critical element in any discussion of the use of clean spaces. For comparison, 50 micrometers is about the limit of visibility with the naked eye, one micrometer (µm) is about 1/100th the diameter of a human hair, and one nanometer (nm) is 1,000 times smaller than that.

As components of products such as semiconductors shrink to sizes thousands of times smaller than the eye can see, cleanrooms have become a necessity for certain high-tech manufacturing, research facilities, and even food-processing facilities. When a single speck of dust can ruin an integrated circuit worth hundreds of dollars, the dedicated air-handling equipment and special durable, static-free surfaces provided with a cleanroom become a good investment. As so-called nanotechnology, the construction of devices and materials at billionth-of-a-meter scales, has grown in the last five years, cleanroom facilities have expanded proportionately. According to *Cleanroom* magazine, the number of cleanrooms in use worldwide has been climbing steadily for the last several years.

Most major U.S. research universities and industrial research facilities in physics, chemistry, or precision engineering operate with some level of cleanroom space. Cleanrooms have become so ubiquitous and essential for quality control that Intel has adopted a figure in a cleanroom "bunny suit" and face mask as its corporate icon for quality. The symbol is even sold as a bean bag figure and as a type of logo on playing cards and other products advertising Intel's Pentium II microchip.

According to the McIlvaine Co. of Northbrook, Ill. (a market research firm that follows the field), cleanrooms and cleanroom equipment make up an $11 billion worldwide market. The primary sectors of this market are semiconductors, automotive, aerospace, food processing, disk drive fabrication, pharmaceuticals, hospitals,medical devices, flat-panel display fabrication, and a variety of applications in research laboratories.

McIlvaine estimates that U.S. industry and science operate approximately 14 million square feet of cleanroom space. According to McIlvaine, approximately 600,000 square feet of this cleanroom space is maintained by the federal government, with the majority under the auspices of the National Aeronautics and Space Administration and the Department of Energy.

NIST provides standard reference materials, calibration services, and measurement methods to all of the industries mentioned above, as well as to the federal and academic research community. NIST total current cleanroom space of about 18,000 square feet represents about 0.13 percent of the cleanroom space available nationally.

Due to the cost associated with the purchase and maintenance of cleanroom equipment and supplies, such as special clothing and air filters, and to the increasing constraints on normal human physical movements at lower (more clean) cleanroom classes, research and manufacturing facilities operate at the least strict level of cleanroom class feasible for specific applications. The wide range of classifications from below 1 to 100,000 allows great flexibility in tailoring specific cleanrooms to specific applications. Cleanrooms rated at class 10 are so free of particles that the equipment within them is frequently operated by remote control or the people inside often use special breathing apparatus and are covered from head to toe in special clothing. Class 100 to 10,000 rooms generally require special cleanroom clothing, but not breathing apparatus. Class 10,000 to 100,000 cleanrooms may look like ordinary laboratory rooms but

use high-efficiency air filters and also may have special ventilation hoods (as illustrated by the picture above), use plastic sheeting to enclose instrument areas, and often use less specialized smocks or procedures to limit particles emitted by people working in the room.

Another feature common to all cleanrooms is controlled airflow. (See cleanroom cross section graphic Appendix A, pg. A4.) As much as feasible, the air in the great majority of higher class cleanrooms is designed to flow evenly from the ceiling down to or through the floor. This helps to ensure that particles generated by people or tools working in the space will be removed quickly from the room air. Controlled airflow also helps maintain constant temperature and humidity, which many cleanroom applications require in addition to clean air. Air pressure inside a cleanroom is also always higher than the air pressure immediately surrounding the room. This difference in pressure ensures that particles and air will flow out of the room at any leaking joints, but cannot flow in with unfiltered air.

Cleanrooms and other specially dedicated clean zones are standard features of research and development laboratories, as well as production facilities, throughout industry and science worldwide. NIST has and uses cleanrooms for its research programs that span almost the entire range of cleanroom classes as well as a wide variety of clean spaces (referred to in the standards literature as "clean zones") within cleanrooms and normal laboratories.

Cleanroom Standards

The internationally accepted definition of cleanrooms and clean zones[1] is rooms or dedicated spaces in which the concentration of airborne particles is controlled, and which are constructed and used in a

[1] "Clean zone" is a term of art with very specific meaning in developing international standards for clean space.

manner to minimize the introduction, generation, and retention of particles, and in which other relevant parameters, e.g., temperature, humidity, vibration, and air pressure, are controlled as necessary.

Clean zones include such things as special instruments, glove boxes, hoods like that illustrated above, and other environmentally controlled spaces; they may be open or enclosed and may or may not be inside a cleanroom.

A space is created and maintained as "clean" by using durable, easily cleaned, and static-free surface finishes; large quantities of filtered air; and special operating procedures (protocols) for personnel. At the highest cleanliness requirements, what the space itself is made of matters. For example, metals such as stainless steel may be ideal for applications involving organic materials but terrible for others involving corrosives materials where plastics must be used. It also becomes important that air flow vertically (laminar flow) from the ceiling down through the floor, and uniformly throughout the room. This continuously "washes" the environment and eliminates eddies and currents that allow contaminants to drop out of the air stream onto sensitive products.

Work done in a cleanroom or clean zone is also very carefully controlled, including the operation of tools and equipment, to avoid creation of dust and debris that would contaminate products and processes. Advanced cleanrooms also require a lot of support

space for air and materials handling. Pictures on this page illustrate a typical class 100 cleanroom (upper right) and the supply, mechanical, and service space needed to support such a facility (lower left).

As demand for cleanrooms and clean zones grows, detailed international standards are continuously being developed, updated, and applied to both construction and operation of clean spaces. Technical Committee 209 of the International Standards Organization (ISO) is working on a comprehensive set of new standards (see Appendix B) governing "standardization of equipment, facilities, and operational methods for cleanrooms and associated controlled environments. This includes procedural limits, operational limits, and testing procedures to achieve desired attributes to minimize microcontamination. Topics of interest are nonviable particles, viable [biological] particles, surface cleanliness, room temperature and humidity profiles, airflow patterns and velocities, room vibration profiles, room light levels, room infiltration leakage, personnel procedures, personnel cleanroom clothing, equipment preparation, and any other topics related to optimizing cleanroom operations."

The ISO standards will address the evaluation, interpretation, and control of biocontamination as well as inert matter, illustrating that cleanrooms and clean zones have applications far broader than in just the semiconductor electronics industry. The ISO standards also deal with much smaller clean spaces, referred to as isolators and mini-environments.

This is an international effort. The American National Standards Institute (ANSI) provides the Secretariat of ISO/TC209, and it is likely that the ISO standards will eventually displace the current U.S. federal standard, known as FED STD 209E.

There is not just a single standard for "cleanliness"—the density of particulate matter that can be tolerated in certified clean spaces can vary by as much as a factor of 100 million, depending on the space's "class." (ISO 1 to ISO 9) There are many kinds of clean spaces, and many different applications.

If a cleanroom or clean zone is to be certified, it must pass three tests. The first and most obvious test is for particle count, which provides the index for the standard. For example, in the current federal standard for a class 1,000 cleanroom, the 1,000 refers to the maximum permitted number of particles of 0.5 micrometer in size per cubic foot. The corresponding ISO class is 6. As might be imagined, the ISO standard uses a metric rather than English measure of air volume. What is more important is that there is an internationally perceived need for a broader range of classifications—the ISO standard adds three additional classes, one dirtier than FED STD 209E class 100,000 and two cleaner than FED STD 209E class 1 in order to deal with evolving industrial needs.

The range of cleanliness permitted by the ISO classes is enormous—ISO 1 permits no more than 10 particles per cubic meter of 0.1 µm in size, and none detectable at 0.3 µm or larger, whereas ISO 9 permits as many as 35 million 0.5 µm particles per cubic meter. Each

step in the classification scale amounts to about a factor of 10 in cleanliness level. ISO 1 is so strict that it is unlikely to be achieved anywhere except in a small glovebox-like environment, while ISO 9 is typical of all the laboratory space in almost any modern laboratory.

The pictures on this page illustrate a common situation—nested clean spaces—in which the cleanroom containing an instrument (an electron beam evaporation system, upper right) or clean zone (a class 10 wet bench inside a class 100 cleanroom, lower left) must be very clean but can be maintained at a lower level of cleanliness than the working volume of the instruments or clean zones themselves.

The other two determinates of a bona fide certifiable cleanroom or clean zone are air pressure difference (the clean air space must be positive relative to the surrounding space, so that contaminants are not sucked in from outside) and airflow (which must be high enough to ensure the integrity of the space's particle count against activities within the room). The ISO standards address these requirements in the design and construction of cleanrooms and associated controlled environments, and in the complete set of tests and their frequency required to demonstrate continued compliance with a certification.

Commonly held notions about the cost and rapid obsolence of cleanrooms are only partly true. Cleanrooms can be expensive compared to general-purpose laboratories, but this applies only for facilities constructed to achieve a certifiable condition at the highest level (class 1,000 to 100 and better). This is because of the above average ceiling heights required for appropriate control of airflow and the most cost-effective three-story configuration usually used (to separate floor areas for gas and waste handling, research activities, and air and exhaust handling).

What can be extraordinarily expensive, due to fundamental building limitations such as ceiling heights, is trying to retrofit room-size cleanrooms to class 100 and better into typical existing laboratory space. (See Appendix A, pg. A4) For this reason, the cleanroom facility in the AML has been designed for, and will be limited to, those programs requiring space that could be certified as at least class 100. It is anticipated that additional needs will be met through refurbishing existing space.

It is well known that rapid obsolescence of cleanroom space is a fact of life in the semiconductor industry. This refers, however, to the very specialized fabrication operations that take place within the industrial cleanroom. The picture at right shows a typical class 1,000 research cleanroom at NIST, which has been functioning well for many years.

Research programs will change and modifications may be needed, but if research facilities are designed with flexibility in mind, changes aren't a major problem. One splendid example of built-in flexibility is the laboratories of the Salk Institute for Biological Studies, which were built in the 1960s and are still running strong. The secrets of its success include generous interstitial spaces and floor-to-ceiling heights that allow multiple "permutations" without affecting the envelope of the superstructure. This build-to-change approach works just as well for research cleanrooms as it does for research chemical or biological facilities. (A similar approach was used for the Advanced Chemical Sciences Laboratory and will be used in building NIST's Advanced Measurement Laboratory.)

The manufacturing equipment in a large-scale specialized semiconductor chip fabrication facility may become obsolete in a few years, but a basic cleanroom can function well for years, even decades, particularly in a research environment.

It should be clear that the word "cleanroom" covers a very broad range of facilities; that cleanrooms are coming into increasingly widespread application; and that certification, or at least the use of established protocols appropriate to a desired cleanroom class, are coming into quite common usage. Cleanrooms and clean zones used by a typical research or development program may span a very broad range of classes and use a variety of protocols as appropriate.

Current Clean Facilities

The clean spaces used in NIST research programs span the entire range defined in the previous section. All NIST programs that use, or need, clean space were revisited in late 1998 to update information for this review. For the purposes of this review, we used the following conventional definitions of space types:

A **Cleanroom** is a room in which the concentration of airborne particles is controlled; which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the room; and in which other relevant parameters, e.g., temperature, humidity, and pressure, are controlled as necessary. This review did not include a detailed engineering study of the rooms in question. If recent certification was not available, the class assigned to the space was based on the user's best judgement, taking into account protocols used to maintain the cleanliness of the room. For the purposes of this review, only spaces at class 100,000 and cleaner were counted.

A **Clean Zone** is a dedicated space in which the concentration of airborne particles is controlled; which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the zone; and in which other relevant parameters, e.g., temperature, humidity, and pressure, are

NIST'S CURRENT CLEANR00M FACILITIES
(Net Square Feet)

	Lab	Cleanroom	Support	Clean Zone	Total Cleanroom and Related Space	Percent Cleanroom and Related Space
Gaithersburg	658,000	12,500	2,800	10,700	26,000	4%
Boulder	109,300	6,000	1,800	10,400	18,200	17%
Total	767,300	18,500	4,600	21,100	44,200	6%

controlled as necessary. This zone may be open or enclosed and may or may not be located within a cleanroom. Typical installations of this type include: HEPA supply filtration units at a research station's air supply, hooded and curtained optical tables, glove boxes, and laminar flow hoods. Some cleanroom attributes such as specific operational protocols and/or special curtains or air handling may be present. If the clean zone is inside a cleanroom, the class attributed to the cleanroom is that of the room itself.

Operational Support Space is the balance of space in the installation, where installation is defined as the cleanroom and one or more clean zones, together with all associated structures, air-treatment systems, services, and utilities. For the purposes of this review, this space includes areas for mechanical equipment, return air, air locks, air handlers, fans, filter units, gowning areas, and storage of cleanroom supplies (gowns, tacky mats, etc.). This space may be in the same room or in adjacent laboratories, but does not meet the definition of cleanroom or clean zone, and directly supports the operation of the cleanroom or clean zone itself.

The technical operating units that comprise NIST's Measurement and Standards Laboratories are organized into 37 divisions (not including the Information Technology Laboratory), 20 of which conduct research programs for which clean space is critically important.

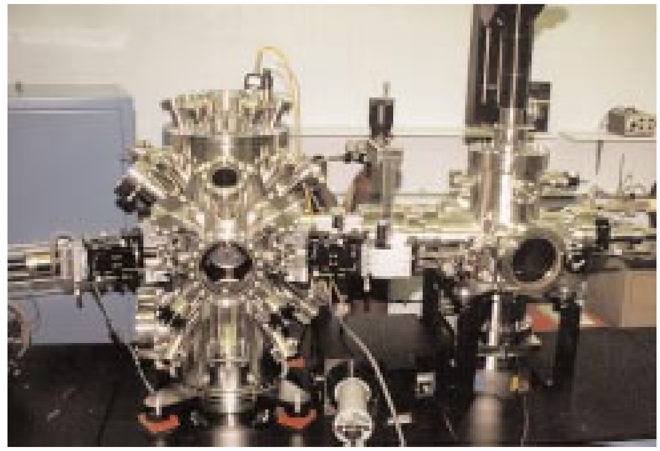
About 12,500 nsf of NIST's current laboratory space in Gaithersburg is devoted to cleanrooms. An additional 2,800 nsf is devoted to operational support space. There are also 19 laboratories that contain clean zones but that are not themselves classified as cleanrooms. This cleanroom and related space is operated by 14 different divisions and located in nine different buildings.

About 6,000 nsf of NIST's current laboratory space in Boulder is devoted to cleanrooms. An additional 1,800 nsf is devoted to operational support space. There are also 19 laboratories that contain clean zones but that are not themselves classified as cleanrooms. This cleanroom and related space is operated by six different divisions and located in two different buildings.

Cleanrooms and their support space amount to about 3 percent of NIST's total available laboratory space (6 percent if the laboratories that house clean zones are included) and are an integral part of the research "equipment" of more than half of NIST's technical divisions.

Unfortunately, about 60 percent of the NIST groups at both sites that use cleanrooms or other clean space for their research programs reported that their current facilities are inadequate to their needs and inferior to comparable space available in academia or industry. Of the remaining 40 percent, roughly half said they had adequate facilities at present but anticipated more stringent requirements in the future. In most cases, it is clear that researchers are pushing the capability of their space to the limit.

The primary limitation to NIST's current cleanrooms at both sites is turbulent, multidirectional, and unpredictable airflow and inadequate air filtration. Air-handling equipment is of varying capacity and serviceability. Maintenance of these systems is difficult because of their age and the number of different types and manufacturers. Clean air may be introduced at cleanroom ceilings to circulate about the room and exit at the walls (ceiling heights do not permit full laminar flow). For lack of space, equipment, benches, and tools are placed against these walls, blocking some of the airflow and creating currents and eddies within the room. The effect is that of creating unpredictably lower levels of cleanliness within any given space. This condition is compounded and rendered more unpredictable when a different user sets up different equipment for a short duration and changes the sources of local contamination and air patterns. The overall effect is one of decreased capability for the space and decreased productivity for the researcher.



Applications and Impact of NIST's Clean Facilities

NIST is responsible for the U.S. national measurement system and for providing measurement traceability to this system. A continuously robust U.S. economy depends on coping with rapid technological changes, for example, rapid decrease in dimensions of all components in integrated circuits; demands for increased manufacturing consistency in pharmaceuticals; and legal requirements for better control of smaller amounts of trace constituents in waste streams. More consensus-based standards and measurement practices are needed to streamline manufacturing processes, particularly in industries that involve contributions from many vendors. NIST is where these standards and measurement-related issues are studied and developed, for "customers" that include not only regulators and consumer product manufacturers but also manufacturers of test instruments, control systems, and NIST-traceable secondary standards.

Dealing effectively with the ever smaller, in either dimension or concentration, means having workspace that is ever cleaner. Presently, more than half of NIST's technical divisions that engage in laboratory research are critically dependent on dedicated clean space of one kind or another. Both the technical programs, and the type of clean space that might be used by any single technical program, cover a very broad spectrum. The following are examples of some of these programs. The examples show why the technical programs need clean space and what parts of the U.S. economy they serve.

(The research described below is based in NIST’s Gaithersburg Laboratory).

Semiconductor electronics is what comes to mind (people in bunny suits with microscopes) when most people think of a cleanroom. The semiconductor industry has been one of the most rapidly growing industries worldwide (more than 15 percent annually for the past 35 years) and is one of the largest industrial users of cleanrooms. The telecommunications industry, as it advances into the wireless age, is critically dependent on semiconductor electronics and on NIST work in this field. State-of-the-art integrated circuit components now are measured in dimensions of less than one µm (100 times smaller than the diameter of a human hair). A motionless person may generate as many as 100,000 particles (skin flakes, salt, oils, moisture droplets, and even deodorant) per minute of a size that may be damaging to integrated circuit fabrication. Throughout the industry, success is now based on quality control of materials and processes, not testing of completed devices.

NIST's thin-film Standard Reference Materials (SRMs) support the entire U.S. semiconductor industry's needs for measuring and controlling the thickness of films in production of advanced semiconductor integrated circuits. The SRMs are silicon wafers of desired thickness (10 to 200 nm) and uniformity (within a one nm band across the wafer). The constraints on dimensional uniformity require cleanliness of at least class 100.

This SRM program is, quite typically, dependent upon NIST's advanced laboratory work, in this case controlled studies of film growth, cleaning, and storage. State-of-the-art films are approximately 2.5 nm thick (10 to 12 layers of atoms), and research is being done on films as thin as 1.5 nm. Industrial need is for measurements and standards accurate to better than 0.1 nm and stable to approximately 0.01 nm. As a result, contamination of the film surfaces, even at the level of a fraction of a layer of atoms, is incompatible with calibrating the measurement systems used to control film production. The picture above shows the ultra-high vacuum spectroscopic tool used for these measurements. It is essential to maintain a controlled atmosphere in the laboratory to protect the integrity of the measurement tool, as well as the measurements and the standards themselves.

As is often the case, clean facilities for storage of test films must be in or near the areas where key measurements are made (the instrument is not transportable) and where supporting research is being conducted.

NIST uses clean space at least class 1,000 (100 to 500 ideally) to make electronic test structure devices from semiconductor material also produced at NIST. The MBE (molecular beam epitaxy) facility for depositing semiconductor layers requires clean space different from that required for making devices (typically transistors). The performance of these transistors is used to better help domestic manufacturers understand their materials problems. NIST also makes non-electrical test structures used in support of programs on fundamental standards. These include atom-based linewidth artifacts used by the industry for manufacturing critical dimension equipment.

The U.S. standard of mass maintained by NIST is depended upon by virtually every industrial sector as well as by a host of federal and state regulatory activities. Customers use these calibrated weights to measure, for example, the amount of drugs in a pill, or grain in a rail car, or the nuclear material in a cask. NIST's clean space (shown below) is used to calibrate mass weight sets for industry, government, and academia to the highest accuracy. The true mass of a customer's weights is determined by comparison to NIST working standards and ultimately to the U.S. standard kilogram and the international kilogram.

Clean space is needed so that the mass of weights that constitute the national standard of mass is not affected by tiny dust particles in the air. At the highest level, sensitivities of 1 millionth of a gram are important.

Ultrahigh vacuum chambers and components are highly dependent on clean space for their assembly. Ultrahigh vacuum systems are specially constructed, ultraclean containers to produce very low-pressure environments. The systems NIST uses can attain pressures below one-trillionth of one atmosphere. Needless to say, the construction of these systems requires the utmost care, attention to detail, and a very clean assembly area. Ultrahigh vacuum systems are used for semiconductor processing, vacuum tube processing, satellite and space simulation testing, in particle accelerators for high-energy physics, and medical imaging systems just to name a few. A vacuum environment is delicate, and the degree of cleanliness directly and negatively impacts the level of ultimate vacuum and the operation of delicate instruments used to monitor the vacuum environment. Even minute impurities and particles can measurably degrade, perhaps even ruin, the vacuum.

MEMS (microelectromechanical systems) devices are miniature sensors and actuators being applied more frequently to measurement and control systems. The colorized micrograph above shows a microrotor similar to those in a miniature motor operated by an integrated circuit. While this microrotor was not made at NIST, the Institute does fabricate a variety of MEMS devices including multijunction thermal converters. MJTC devices are used for more accurate current and voltage calibrations. These devices currently have 15 µm lines with 10 µm spaces (about 10 to 15 percent of the diameter of a human hair) as their smallest dimensions.

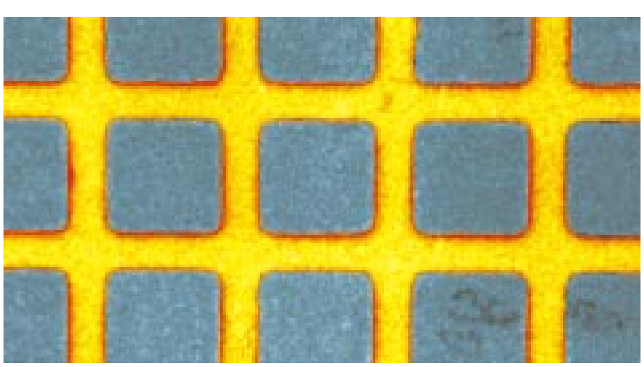
Testing for performance and reliability of all these MEMS devices involves measuring not only their electromechanical properties but also the contours of surfaces on devices, such as the film-strain sensors, that accomplish their measurements by deforming.

Clean surfaces at class 100 are critical for the testing as well as the production of some of these MEMS devices, and class 1,000 may prove to be inadequate for more of these systems as this work progresses to smaller, more sensitive devices.

Laser-based measurements of all types are increasingly dependent on the maintenance of clean conditions in and around the experimental space. Laser optics exposed to room air in conventional labs degrade measurably within hours. Dust scatters the laser light, adversely affecting the stability of the lasers and adding uncertainty to the measurements.

For example, NIST uses the filtered air lab modules for keeping optics clean in focused laser atom optics research. This work uses laser beams to manipulate atomic beams and generate small microstructures whose dimensions are tied directly to the wavelength of the laser light. This offers the promise of one day making integrated circuits or other microfabricated objects about 10 times smaller than is possible with light-based lithography methods. The colorized graphic below shows a grid of gold lines drawn on silicon using an earlier version of this atom lithography technique. The lines are a few µm wide, with extremely sharp edges (less than 100 nm of roughness).

Near-field optical microscopy is being used to develop new techniques that expand beyond the limits of ordinary microscopy. This kind of work is often done in a clean hood. The use of thin films or coatings to solve outstanding problems in fields such as tissue engineering, nanoscale chemical systems, or organic electronics is limited by the homogeneity and nanoscale properties of these films. Conventional technology for investigating these structures often involves methods that are destructive or that are sensitive only to average or bulk properties, not to the nanoscale variations in these features.



While ordinary microscopy can measure feature sizes down to about 300 nm, near-field microscopy is capable of 10 nm resolution. Since 10 nm is 10,000 times smaller than the diameter of a human hair, cleanliness of the samples is extremely important.

It is impossible, moreover, to make near-field microscope probes, which consist of small glass fibers sharpened to a 20-nm point, then coated with aluminum, in ambient air—a single piece of dust on the probe destroys it. Each probe takes roughly two hours to make, and NIST makes approximately 100 probes in a year. A clean area (class 5,000 or better) is essential to this work.

Advanced optical devices and measurements do not always employ lasers or microscopes. Clean spaces are used for assembly and testing of a new class of optical devices that measure chemical species in condensed phases. These devices have potential use for remote detection of ground water pollution, for analysis of hazardous materials in sealed nuclear waste containment vessels, for microanalysis of biological materials, and for fundamental measurements of chemical reactions at interfaces. The devices contain small gaps through which light passes in amounts determined precisely by the gap-width. Since the gaps are smaller than the diameter of most dust particles, any dust particles sandwiched into the device during assembly would prevent proper operation. Furthermore, if the device were constructed with a dust particle obstructing the light path, the device would not operate and probably suffer damage. A class 100 work space would be best for construction of these devices—although NIST currently uses a class 1,000 environment with moderate success.

The NIST Low Background Infrared Radiation Facility shown on next page serves as the U.S. standard for infrared sources used to calibrate space-based detectors aboard missiles and satellites. A cleanroom is used to surround the equipment for low background infrared experiments that use chambers equipped with special optics and detectors cryogenically cooled to 20 K, in order to eliminate all extraneous background heat radiation. NIST uses space class 10,000 or better to store filters, mirrors, and SRMs and to keep the black paint in the vacuum chambers dust free.

Advanced optical measurements of almost all kinds (with lasers, microscopes, sensors, and

other specialized optical devices) require clean spaces not only to avoid interference with tests (e.g., light scatter and contaminated data) but also to protect the integrity of the instruments and optics.

Light-scattering measurements are used to characterize particles, defects, and roughness on silicon wafers and other high-quality optical surfaces. The semiconductor, flat-panel display, computer disk, and optical industries use the results of this research to improve methods for optically inspecting materials for defects that otherwise would decrease their production yields. Any material, when exposed to untreated air, will accumulate particulate matter. NIST typically performs a large number of measurements over a period of several days for any particular sample. Since particles are deposited intentionally, in sizes that are usually much smaller than those found in untreated air and much better characterized, contamination from outside sources would render measurements useless. Sufficient cleanliness (class 10) must be maintained to assure that no contamination occurs during a test.

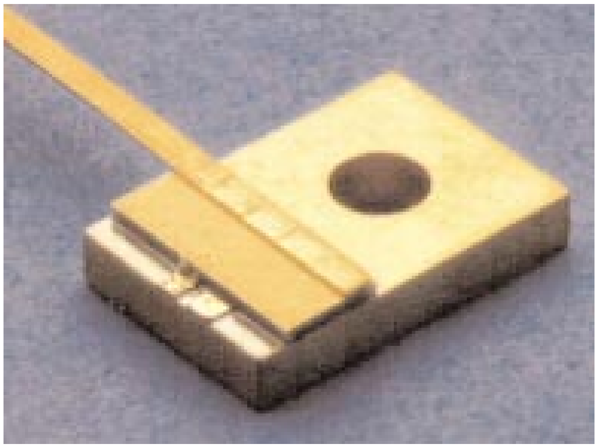
Light-scattering techniques also are used along with mass spectrometry in the certification of polymer SRMs. Polymer producers and processors use these standards to calibrate chromatographs employed in quality control. Particulate matter interferes with the quality of light-scattering measurements by contributing significantly to background scattering. Mass spectrometry on polymers is conducted using a technique where bursts of laser light are used to volatilize a miniscule portion of the sample. Contamination of the sample by particulate matter during preparation and loading into the spectrometer significantly reduces quality of the data.

Microparticle analysis, manipulation, control, and characterization require some of the cleanest environments obtainable. Typical projects are contamination investigations for the semiconductor industry and forensic microanalysis of samples for the International Atomic Energy Agency (IAEA). Data determined from IAEA samples may be used as evidence in a signatory country's claims, ultimately with regard to the proliferation of weapons of mass destruction. It is imperative that samples are not cross-contaminated and that other materials present in the local environment and laboratory do not contaminate the evidence for obvious international political reasons. NIST's microanalytical challenges include the ability to detect only one microscopic particle of interest among many billions that may be present in a single sample. To be able to achieve this capability, clean air and surface environments must be maintained during the handling and preparation of these samples. This requires class 1 to class 10,000 levels of cleanliness, depending on objectives and procedures.

Trace and ultratrace analysis involve exquisitely precise determination of the composition of materials. Trace components of materials are defined as those below 100 ppm; ultratrace is defined as components below 1 ppm. Ultratrace chemical analysis supports both industrial needs and provides quality assurance of chemical measurements used to assess and improve public health, safety, national security, and the environment. NIST SRMs for uranium and asbestos are typical products of this kind of research. These exacting measurements can be limited by contamination in the sample handling/measurement process. Especially clean space is required because a single particle of dust (with a mass of a few billionths of gram) falling into a sample or reagent container will contaminate the sample or reagent and compromise the ability to make accurate, meaningful measurements.

NIST must be able to detect and characterize materials at some of the most extreme levels of ultratrace analysis imaginable and to perform single particle analysis and micromanipulation at the limits of detectability. This work requires a highly filtered, exceptionally clean working environment.

Advances in analytical instrumentation also drive the need for clean space. NIST's state-of-the-art instruments are so sensitive that all samples must be diluted to 100 ppb or less to allow quantitative measurement. This makes every measurement an ultratrace analysis and puts increased emphasis on the quality of the laboratory environment and of the reagents and containers used.



(The research examples described below are based in NIST's Boulder Laboratories).

DC and AC voltage standards fabricated in a class 100 cleanroom at NIST are the most complex superconducting circuits in actual use. These circuits provide the vast majority of the world's precision knowledge of voltage. NIST staff also use these same cleanroom facilities to fabricate world-leading capacitance standards, X-ray detectors, infrared detectors, optical power sources, precision microwave devices, and mass spectrometry detectors. A radically new capacitance (the measure of a capacitor's charge-holding ability) standard may be built on the world's most accurate electron counter, illustrated in the colored micrograph at right. The bullet-shaped regions in the center are µm-sized islands of aluminum whose capacitance is so small that at temperatures near absolute zero only one electron can occupy an island at a time. This microcircuit can "pump" 70 million electrons onto a capacitor, one at a time, with an uncertainty of just one electron.

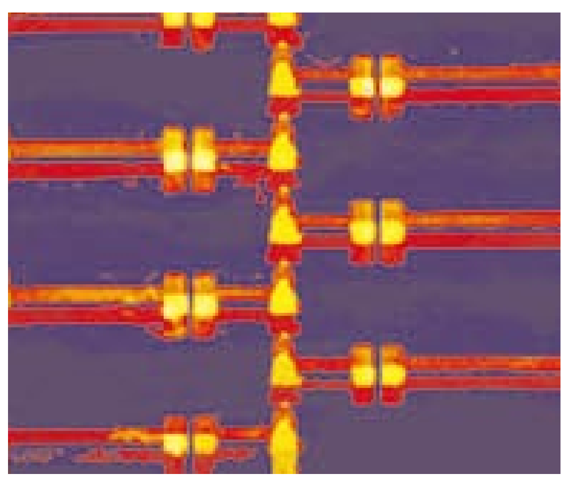
To fabricate complex and very small state-of-the-art NIST standards in integrated circuit form, a space free from dust must be provided. The dimensions of these devices range from 10 percent down to 0.1 percent the diameter of a human hair. Even one tiny speck of dirt can obliterate a critical feature of one of these circuits.

Class 100 is sufficient for NIST's present work when accompanied by clean hoods at class 10. In the future this work may require class 10 or better.

Diode lasers developed at NIST are used for time, frequency, and length metrology. These narrow-line-width lasers are used to manipulate the motions and internal states of atoms in atomic clocks, atomic frequency standards, and optical wavelength reference standards. One part of the processing done with these lasers is the coating of facets of small diode lasers to optimize for the transmission of light at a particular wavelength. These diode lasers can be extremely small, as the graphic at left shows. (The picture is mostly the heat sink—the diode laser is the very small item on the middle of the step on the left. It is approximately square and about 500 µm on a side). Thus, exceptional cleanliness is needed to ensure the integrity of the coatings. The number of applications requiring specialized diode lasers has been growing rapidly in recent years, and that growth is projected to continue. NIST foresees an increased need for diode laser systems in length metrology, advanced atomic clocks, monitoring of pollutants in the atmosphere, and advanced analytical chemistry.

High-speed integrated circuits for the microwave industry is a burgeoning field. NIST fabricates integrated circuit transmission line test structures for use as calibration references for microwave and radio-frequency measurements. The dimensions of the transmission line structures range from 5 to 100 µm in linewidth, and so cleanroom facilities are necessary for developing special test artifacts that enable the advancement and commercialization of new technology by the microwave and integrated circuit industries. The artifacts enable NIST to develop and characterize the special measurement procedures and test structures (SRMs) necessary for industry to perform reliable measurements on both prototype and production integrated circuit wafers.

Optoelectronics is the marriage of optics and electronics and is the key technology in applications ranging from telecommunications and data communications to displays, optical data storage, laser sensing, bar-code scanning, printing, medicine, and machining. Integrated optoelectronic circuitry combines the functionality of electronic integrated circuits with the generation, modulation, switching, and detection capabili-

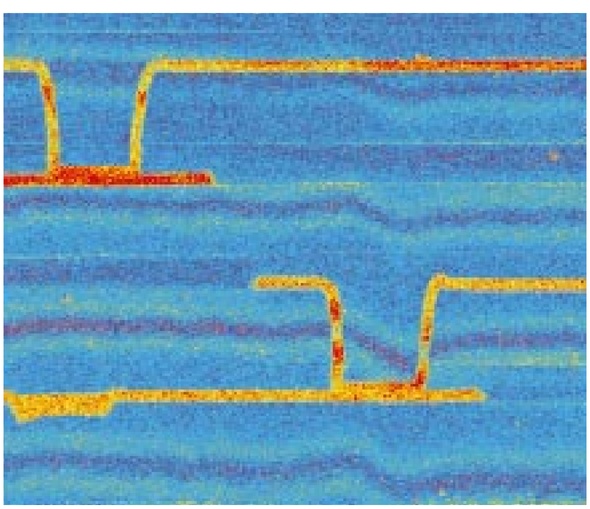


ties of light. NIST grows, processes, and characterizes semiconducting and dielectric materials that industry uses to understand the effects of changing the fabrication parameters on the device performance and to develop measurement methods to better characterize the devices during fabrication. As an example of industry's use of the work, a glass manufacturer has optimized laser glass compositions and offered new commercial products based on laser fabrication and measurements by NIST.

Many of the key devices used in optoelectronics have µm-scale feature sizes in the lateral direction and/or nm-scale feature sizes in the material growth direction. Because of their small feature sizes, sub-µm resolution and very high levels of cleanliness are required to fabricate test devices and achieve high yield and reduce costs.

The small feature size of lasers, about one µm, sets the requirements for the number and size of contaminant particles tolerable in the cleanroom. Class 10 or better is common in the cleanest fabrication space in an industrial environment. Because NIST is not as concerned for production reproducibility, class 100 is acceptable.

Electron microscopy is a tool used widely at NIST. One application is in studies of the mechanical, thermal, crystallographic, and magnetic properties of the components of microelectronic devices, both the separate materials (metal lines connecting transistors on a chip), and the packages, which contain many transistors, many levels of metals and ceramics, as well as various structural and adhesive elements. NIST's main effort is to determine the effect of stresses that occur in processing and in operation on the reliability of these structures and to transfer measurement techniques to the semiconductor and packaging industries.



One promising method is electron beam moiré (illustrated by the colored micrograph at right), a way to image strained areas before and after heating so that the design of interconnects can be improved. At present, NIST uses cleanroom facilities for creating test samples and for preparing samples provided by collaborators, which frequently involves removing layers from a structure, depositing layers, or both. The next (or next-next) generation of structures will be so small, on the order of 200 nm, that optical microscopy will be useless and particulate contamination a greater and greater problem.

Configuring Cleanroom Facilities for the Future

We are living in an age in which semiconductor devices shrink to half their previous size every three years, and scientific advances depend on microscopic techniques not only to "see" but to manipulate and actually fabricate new structures with individual atoms. Electronics already are being constructed with dimensions of tens of nanometers. According to industry experts, within 10 years microsensors produced via nanotechnology are expected to replace nearly every kind of existing sensor, creating a market of several billion dollars. The impact of these sensors will be even greater. Pharmaceutical companies, for example, are eager to use arrays of microsensors to evaluate hundreds or even thousands of new drug formulations almost instantaneously. Such rapid screening holds potential for addressing the $100 billion to $200 billion worldwide market for new therapeutic drugs.

NIST research helps foster this kind of technological innovation, the driving force for about 50 percent of U.S. economic growth. A ruler, whether it measures millimeters or nanometers (billionths of a meter), can be only as accurate as the template used to make it. NIST's job is to provide U.S. manufacturers and scientists with "gold standard" templates that are indispensable to enable new generations of science, technology, and competitive products. NIST must be the best at measuring a whole range of quantities because industry needs high accuracy, and it is clear from the foregoing that NIST is invested heavily in a very broad range of measurement and standards activities that depend on clean spaces of one kind or another.

If the United States fails to address the facilities issue in its national measurement laboratory, other countries that already have invested heavily in their measurement laboratories will be moving ahead, providing their industries with a competitive advantage over American firms. A recent NIST benchmarking study of measurements and standards laboratory programs in Germany, Japan, and Brazil found that all three countries recognize the importance of metrology for economic growth, industrial and scientific leadership, and competitiveness. All three recently have increased their funding for measurements and standards programs, and all have strong construction programs for laboratory facilities substantially better than those currently available at NIST. For example, NIST's German counterpart (the PTB) recently completed a major cleanroom facility for electronics and dimensional metrology. In some cases, buildings or facilities built as recently as five to 10 years ago already are being renovated. The United States is the world's most advanced industrialized nation with the highest standard of living, but our competitors are catching up fast. The U.S. industrial and scientific communities cannot afford to settle for a second-rate measurement system.

The aggregate effect of NIST facilities' inefficiencies, which include the lack of adequate cleanrooms and other clean spaces, on the U.S. economy is large. More than a dozen economic impact studies of NIST programs have been conducted in recent years. The benefit/cost ratios determined for the programs studied ranged from 3:1 to more than 100:1, with a representative ratio of approximately 10:1. In other words, for every dollar spent on NIST research in the studied areas, benefits of $3 to more than $100 were realized by the U.S. economy.

Cleanrooms amount to approximately 3 percent of NIST's total available laboratory space (6 percent if the laboratories that house clean zones are included), and are needed by technical programs in more than half of NIST technical divisions. Their use is growing, and the cleanliness levels required are steadily increasing. What used to be done in a class 10,000 environment now requires class 1,000; last year's class 1,000 laboratory is no longer good enough for this year's class 100 project, and so on. Ideally, every group that requires a high-quality cleanroom could have one right at hand, convenient to the other elements of its research program that either support, or depend upon, the work going on in the cleanroom. A cleanroom activity is usually only one element of a research project, and moving test materials, equipment, or people from one area to another brings with it obvious risks to the cleanliness of the entire enterprise. But complete programmatic adjacency at the highest levels of cleanliness is just not feasible within NIST's constrained budget.

The solution is limited construction of new centralized cleanroom facilities for the class of user that requires the highest level of cleanliness. Because of the demands of modern technology, these facilities will be used very heavily.

The cleanroom planned for the AML will have approximately 12,000 nsf of clean floor, increasing the total cleanroom space in Gaithersburg to about 24,500 nsf. The design of the AML includes all the features (including generous interstitial spaces and floor-to-ceiling heights) that will allow the labs to be upgraded easily and, therefore, avoid rendering the facility, including its cleanroom component, obsolete in just a few years.

In the needs assessments conducted over the last 10 years (see Appendix B), requirements for additional high-quality clean space in Boulder consistently have been found to be comparable to those in Gaithersburg. To minimize cost, NIST intends to meet them using the same approach, i.e., limited construction of centralized facilities.

To consolidate those Boulder programs requiring regular use of high-grade cleanroom space at the Gaithersburg site would require more than doubling the size of the cleanroom space currently planned for the AML. Moreover, several of the Boulder divisions needing better cleanroom space have specific geographic ties to the Boulder area. The electromagnetic field group uses electromagnetically quiet space in Boulder, unique in the United States, to conduct some of its experiments. The optoelectronics group has well-established technical linkages with the extremely active telecommunications industry along Colorado's Front Range. The time and frequency group not only conducts cutting-edge laboratory work but also maintains the U.S. satellite link with Asia (not possible from the East Coast) essential for international time transfer and maintains NIST's radio tower that broadcasts official NIST time to the entire country from centrally situated Ft. Collins, Colo.

NIST concludes that it would not be programmatically sensible, cost-effective, or technically appropriate to consolidate all NIST programs requiring regular cleanroom use at one site.

- ***It would produce no significant increase in technical synergy between NIST programs.***

- ***It would entail significant net cost, in dollars, program disruption, and intellectual assets, to relocate even the minimum number of technical staff.***
- ***It would require the construction of a separate new cleanroom facility in Gaithersburg, plus additional office and laboratory space.***

NIST's facilities improvement plans include the building of a general-purpose high-grade cleanroom facility at both its sites because the need for clean space pervades modern technology. The general nature of these facilities, and the flexibility to be designed-in, will preclude rapid obsolescence.